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Perception and action: Approach to convergence on embodied cognition

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지각과 행위: 체화된 인지와의 융복합적 접근

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Abstract Space perception is generally treated as a problem relevant to the ability to recognize objects. Alternatively, the data from shape perception studies contributes to discussions about the geometry of visual space. This geometry is generally acknowledged not to be Euclidian, but instead, elliptical, hyperbolic or affine, which is to say, something that admits the distortions found in so many shape perception studies. The purpose of this review article is to understand perceived shape and the geometry of visual space in the context of visually guided action. Thus, two prominent approaches that explain the relation between perception and action were compared. It is important to understand the fundamental information of how human perceive visual space and perform visually guided action for the convergence on embodied cognition, and further on artificial intelligence researches.

Key Words : Convergence, Embodied cognition, Perception-action, World model approach, Control law approach

요 약 공간 지각은 일반적으로 물체 (형태)를 인식하는 능력에 대한 문제로 여겨진다. 대안적으로, 형태 지각 연구는 시각 공간의 기하학에 관한 논의에 기여한다. 이러한 공간의 기하학은 일반적으로 유클리드가 아닌, 타원, 유사성, 또는 아핀 (affine) 기하학으로 알려져 왔다. 다시 말해, 많은 형태 지각 연구들에서 보여 왔듯, 공간은 변형된 기하학으로 지각된다. 이 논문의 목적은 지각된 형태와 시각적으로 유도되는 행동과 관련된 시각 공간의 기하학에 대한 이해를 돕기 위함이다. 따라서 지각과 행위의 관계에 대해 설명하고 있는 두 이론을 비교해 본다. 체화된 인지와 더 나아가서, 인공 지능 연구와의 융합에 있어서 이러한 인간의 기본적인 공간 지각 능력과 시각적으로 유도되는 행위를 먼저 이해하는 것이 중요하다.

주제어 : 융복합, 체화된 인지, 지각-행위, 위계-표상 모델 접근법, 협응-조절 접근법

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1. Introduction

Embodied cognition is generally defined as that many features of human cognition are shaped by aspects of the body beyond the brain. The features of cognition included high level mental constructs and human performance on various cognitive tasks. The aspects of the body include the motor system, the perceptual system, and the body′s interactions with the environment. Embodied cognition is, importantly, related to artificial intelligence regarding of event perception[1]. Lee[1] reviewed two event perception theories to understand the fundamental information of how human perceive event perception to converge on robotics. To develop artificial intelligence more efficiently, it is important to understand the embodied cognition, that is, the relation between perception and action and the interaction with the environment. In this article, the aspects of the body, specifically perception and action system was reviewed.

Numerous shape perception (space perception) literatures have provided strong evidence that 3-D structures cannot be accurately perceived and there are only the non-Euclidean and ordinal relationships between physical and perceived space. The recovery of Euclidean structure cannot occur in the perception of structure from motion[2,3,4], the perception of structure from binocular stereopsis[5,6], the perception of structure from combination of stereo and motion[6,7] and even under full cue conditions[8,9]. It is important to keep in mind that although there are many sources of optical information to perceive 3-D structure, neither a single individual source nor a combination of sources is enough for accurate perception of 3-D structure. However, it could be possible that the laboratory environment is constrained compared to our natural environment, thus other crucial sources of optical information are missed in the experiments.

Börjesson and Lind[10] found that there was no difference between parallel and polar projection for the perception of Euclidean structure, but they also examined the possibility of polar projection with large visual angles for the perception of Euclidean structure. Observers perceived the depth dimension more precisely at the large visual angle, but Euclidean structure was not recovered since the height was still underestimated even at the large visual angle. They concluded that the observers can use additional information from the polar project with the large visual angle, although the recovery of Euclidean structure was not yielded by the addition of polar information. Also, they suggested that the visual system might be limited when trying to perceive Euclidean structure because of the noise in the measurements of retinal velocities. Under small visual angles, a very small noise while measuring retinal velocities produces great errors. For instance, Koendreink and van Doorn[11] have shown that if the visual angle is less than 15° and the measurement noise variance is 5%, it is nearly impossible to recover Euclidean structure.

Now, the question is how humans can perform complex visually guided actions very accurately and trivially despite the fact that perceived space is not accurate? The solution to this question is two fold. First, shape perception might not be directly relevant for guidance of actions. Second, shape perception might be closely related to actions. Therefore, desired behavior arises from the perceptual-motor mappings that tweak the dynamics of the system. In respect to these two questions, there have been two theories: world models and control laws in perception and action.

2. Two theories in perception and action

2.1 World model approaches

From model-based approaches, perception is mediated by the required sensory input. The optical stimulus gets into the sensory organs and then the central nervous system internally constructs the relation between visual space and physical space by processing the optical stimulus. In other words, the visual percepts (visual space) of the surrounding environment are internal representations of the external, physical space. These representations are the combination of input to sensory organs and processing by the central nervous system. The internal representation of the environment can be maintained and can support continued action even when every kind of stimulation (e.g., visual, auditory, or haptic) from the environment is not temporally provided. Effective control of complex action requires not only the perceptual representation of the environment, but also an internal model of the dynamics of the action. The dynamic behavior of the motor system involving planning, control, and learning is copied through the internal model constructed by the central nervous system. This process is called efference copy. Internal assumptions and expectations based on past experience play an important role to control actions. Once a person acquires the internal model of the dynamics of the action with extensive practice, the motor system executes the motor command for specific actions with ease. In addition, functionally similar actions could be performed by transferring from the flexible internal model and by being modified by parametric adjustment[12].

There have been proposed two prominent internal models of the dynamics of the physical system. First, inverse models invert the direction from the sensory encoding process to the output process. They compute the motor command that is predicted to yield a particular state transition from desired sensory consequence into the motor action. Inverse models are a fundamental module in open-loop control systems (action without continuous vision). The example of an inverse model is vestibulo-ocular reflex (VOR). To keep eye gaze fixed in space, the VOR couples the movement of the eyes to the motion of the head. Once the head is moved, the movement of the eyes is in opposite direction to the motion of the head to fix the gaze. The VOR control system computes the motor commands which yield the motion of the head. Then, this computation yields a particular retinal velocity to produce the movement of eyes. Thus, even when the visual stimulus is not continuously available, it is possible to fix the gaze in the VOR inverse model[13].

The second internal model is the forward model in motor control. While inverse models invert the system by providing the motor command which will produce the desired change in state (i.e. desired movement) given the current state of the system, forward models of the physical system predict the movement outcome given the current state of the system and the motor command. Forward models are useful for rapid movements because the movement outcome can be estimated and used before available sensory feedback. For example, when catching a ball the information on the ball's trajectory and possible placement of the hand are sensory information received in advance and fed forward by an efference copy of the motor command. Wolper, Ghahramani, and Jordan[14] developed the Kalman filter model of the sensorimotor integration process based on the information available from proprioception and the efference copy of the motor command to estimate the arm's final configuration in the absence of visual feedback. The first feedforward process allows estimating the next state using the efference copy along with the current state. The second feedback process allows correcting the next state estimated by the forward model using the difference between expected and actual sensory feedback based on the current state. For instance, when the forward model overestimates the distance traveled due to the overestimated force acting on the arm, the Kalman filter model balances the final estimate by the sensory correction of the feedback process.

In addition to the theoretical research, empirical research supports world model approaches which propose perceptual representation of surrounding physical space and internal models for the dynamics of physical system. Loomis, Da Silva, Fujita, and Fukusima[15] performed experiments with two different tasks: visual judgment of interval distance (matching) and visually directed action (walking) tasks. In a matching task, observers binocularly viewed two fixed targets which created a frontal interval of 1.0, 1.5, or 2.0 m symmetrically placed about the central axis on the ground. They then had to adjust the length of a depth interval of two markers along the central axis so as to appear equal in length to the frontal interval defined by two targets. Two assistants moved the variable marker following the observer's verbal instruction. The distance from the observer to the targets varied from 4 to 12m by 2m. In a walking task, observers viewed the target positioned along the line of sight binocularly with fixed head position, then closed their eyes and walked to where they thought the target was. The variance of distance was the same in the matching task. The results of the two tasks were quite different. In the interval matching task, observers judged the length of the depth interval larger than the length of the frontal interval. As previous space perception studies have shown, inaccurate performance for the depth intervals increased with the viewing distance. However, observers accurately walked toward the target with closed eyes. In addition to walking toward the target with closed eyes, observers continued correctly pointing to the target positioned on the side while walking along straight paths that passed off to the side with closed eyes. These results have shown that inaccuracy in perception of physical space does not matter in the visually open-loop motoric tasks because outcome of movement is yielded by motor command of internal model.

Fukusima, Loomis, and Da Silva[16] investigated a more complex walking task without vision. Observers viewed a target and then walked with closed eyes along a straight path in the direction oblique to the target. They were asked to turn and walk toward the target from an experimenter. They walked accurately toward the target in spite of having no knowledge of when to turn. Fukusima et al.[16] suggested that observers update a spatial image of the location of previously viewed targets. However, they also found that the accurate performance occurred only within 15m and at a farther distance, observers under-walked to targets. They noted that observers cannot calibrate their walking to be accurate for the targets located at the far distance because visual cues of distance are restricted from afar. Similarly, Philbeck and Loomis[17] found that observers walked to targets accurately when targets were presented on the floor, but over-walked to near targets (e.g., 0.5m) and under-walked to far targets (e.g., 4m) when targets were presented at eye level.

In sum, the basic concept of world models is explained with the following four concepts: (1) sensory input (2) representation of physical space (i.e., encoding process) (3) internal model for planning action (i.e., output process) (4) desired action. After the representation of physical space from sensory input is constructed, even when sensory input is interrupted (e.g., by closing the eyes), desired action is successfully continued because spatial images created by the encoding process and the output process mediate desired actions.

2.2 Some limitations of world model approaches

The world model theory could have some limitations. First, Fukusima et al.[16] and Philbeck and Loomis[16] found that observers did not walk to targets accurately without vision when the target was presented at the far distance or at eye level. They claimed that the distance cue is restricted, thus it is difficult to calibrate walking to be accurate under this restricted condition. According to these results, world models could work only when sensory input is accurate. However, as shown in the space perception literature, we cannot perceive Euclidean 3-D structure accurately and the depth dimension is problematic. We generally overestimate at the near distance and underestimate at the far distance. How could they say that sensory input is accurate at the near distance? Also, how could a “restricted” visual cue be defined within world models? In other words, how could the critical point of “near” distance be defined? Is the visual cue restricted when the target is presented at the half height between eye level and the floor? If the internal model commands the action by calibrating from the sensory input, why does sensory input have to be accurate? Also, the environment of experiments could be constrained because observers know that the floor is flat and there are no obstacles on the ground. According to world models, even when the environment is clustered with objects we could act without vision because we internally encode spatial layout and plan the action. Could this be possible within internal representations of physical space and internal models for the dynamics of action? World model theorists could claim that lots of experience makes it possible. However, what if the action is suddenly interrupted? It is difficult to explain how behaviors governed by internal representations interact with the environment. Such considerations have led other researchers to find another way to explain the relation between perception and action.

2.3 Control law approaches

The relation between shape perception and the guidance of action is explained by a control law which is considered to be “a mapping from task-specific informational variable(s) to action variable(s) that describe observed behavior” ([18], pp. 309). The control law can be expressed as a function in which informational variables modulate the control variables of a dynamical system:

$$\mathring{a} = \Psi (a, i),$$

where **a** is the current state of the action system and **i** is a vector of informational variables. In other words, the informational variables regulate the control variables of the action system and perceptual-motor mappings tweak the dynamics of the action system to produce the desired behavior. The behavior of the action system is described as changes over time. The control law does not indicate the kinematics of the movement itself, but rather it specifies an attractor for the action system which is a location that trajectories converge to from different initial conditions. The information modulates the dynamics of the action system by generating effector forces. The effector function converts the control variable into muscle activation and limb movement given the properties of the musculoskeletal system. To modulate the action system, the informational variables need to be dimensionally matched with control variables. In addition, since the informational variables have higher order relations among many elementary variables, and the control variables also have higher order relations among many degrees of freedom of the musculoskeletal system, low-dimensional information variables must map to low-dimensional control variables to simplify the control problem. The applicable example is the relation between the optic flow pattern and heading locomotion. On the information side, a global flow pattern is formed by many elementary local motions, including a focus of expansion. High-dimensional local motions are compressed into a low-dimensional variable, the focus of expansion which specifies the current heading direction. On the action side, many degrees of freedom of the musculoskeletal system are compressed into gait patterns which behave as a low-dimensional dynamical system with a few free control variables. Among these free control variables is the direction of force applied against the ground which determines the current heading direction. Thus, informational variables are matched with control variables in the same term with respect to the current heading direction[18,19].

Control law theory lays in contrast to world models which propose that perception is mediated by sensory inputs through internal representation and the intended action is planned and controlled by the internal model of the dynamics. The control law approach denotes that perception and action are coupled and perceptual-motor mappings tweak the dynamics of the system for the desired action.

Loomis and Beall[12] argued that an internal model of the dynamics of action would be supported by findings that actions such as walking toward the target are accurately performed even after vision is removed. However, it has been found that performance on driving tasks[20,21] and on reaching-to-grasp tasks [22,23,24] degrades sharply without vision. Wallis et al.[21] found that participants could not continue accurate steering movements without vision, resulting in systematic errors in final heading. Their errors reduced when visual feedback was presented at the end of each trial. It has been shown that the perceptual-motor mapping should be calibrated by feedback. In a similar vein, Bingham et al.[23] found that regular haptic feedback corrected inaccuracy and instability of reached distance and object size during reaching-to-grasp tasks without vision of the hand (open-loop control). Also, they found that haptic feedback has stability which results in no difference for the effect of haptic feedback on calibrating reaches-to-grasp between when feedback was presented for full time (every trials) and for 50% of time. That is, haptic feedback drifts away after time but regular haptic feedback within a period of time is enough to calibrate perceptual-motor mappings. This can explain the success of walking without vision in the studies of Fukusima et al.[16]. Fukusima et al.[16] found that the accurate walking without vision occurred only within 15m, not at a father distance. If the distance or the period of time is short, feedback might not be needed to calibrate the perceptual-motor mapping, but after the period of time feedback should be needed.

The proposition of the control law in which calibrated perceptual-motor mappings tweak the dynamics of the system for the desired action has also been supported by studies on locomotion[25] and reaches-to-grasp an object tasks[26] in which participants are recalibrated using distorted feedback. Ooi et al.[25] investigated whether the mapping between distance and walking determined by the angular declination could be recalibrated by base-up prisms. The visual system uses the angular declination below the horizon with the trigonometric relationship from the eye height and eye level for distance judgment. First, participants viewed the target binocularly through base-up prisms which increased the angular declination, then walked toward the previewed target in blindfold. Due to the increased angular declination, participants underestimated the distance. Then, after viewing the target without prisms, participants walked again toward the target in a blindfold. At this time, they overestimated the distance because of the after-effect of base-up prism adaptation. In other words, prism adaptation recalibrated the eye level downward thus the angular declination below the horizon was also reduced after prism adaptation. Mon-Williams and Bingham[26] investigated whether distance and size perception can be recalibrated by distorted haptic feedback for reaches-to-grasp. In this study, participants could view the targets, but could not view their hand (open-loop control). After given the distorted haptic feedback, the participants reached to grasp the virtual objects as if they really grasped the objects, but without touching the objects. The distorted haptic feedback recalibrated distance and size perception during reaches-to-grasp. For instance, when observers got distorted, shorter haptic feedback than correct distance participants, they underestimated for all distances such that they generalized all distances shorter over reach space.

The perceptual-motor system is task-specific such that the system may use different information for different tasks. For instance, global radial outflow might control heading toward a target point[27], the temporal derivative of tou (tou-dot) might control braking[27,28], the temporal derivative of time to balance might control stabilizing under unstable situations (e.g., when the subway or the bus suddenly stopped)[29], and so on.

Since the information is specifically and tightly coupled to particular aspects of action, each action should be modulated by perceptual-motor mapping in a different way. Rieser, Pick, Ashmead, and Garing[30] investigated whether walking and throwing toward the target could be recalibrated independently. First, participants repeatedly walked or threw a beanbag toward the targets while their eyes were blinded until their performances were stable and accurate. Then, they walked on a treadmill towed behind a tractor on a low trailer. The trailer was towed at speed faster (or slower) than the speed of treadmill. Since the trailer speed was different from the treadmill speed, optic flows to which participants were exposed were not appropriate to their walking but were faster (or slower). After walking on the treadmill, participants performed both a walking and throwing task again. While participants threw the beanbags to the targets accurately, they under- or overshot the target distances when they walked toward the targets. Thus, walking toward the targets was recalibrated by optic flows produced by the difference of speed between the trailer and the treadmill, whereas throwing to the targets was not affected. Next, participants rode on the trailer and threw beanbags to targets while the trailer was towed toward (or away from) the targets. After throwing on the trailer until their performance was reliable, participants performed walking and throwing tasks again. When throwing the beanbags to the targets on the ground, they under- or over-shot the targets while their walking remained unaffected and accurate. These results have shown that the dynamic system of walking and throwing is recalibrated independently because dynamical properties of the anatomical structures including muscles and bones are harnessed to produce deterministic dynamics used to perform specific tasks. “For instance, walking is achieved by organizing the legs to function as a combination of upright and inverted pendulums, whereas throwing is accomplished via a combination of a mass-spring and whiplike dynamics.” ([31], pp. 1046)

So far it has been found that one of the ways for perceptual-motor mappings to tweak the dynamic system for the desired action is through calibration by visual or haptic feedback. Another way to modulate the desired action is online guidance. Some actions (e.g., reaching-to-grasp the object shape) could not be calibrated by feedback. Lee, Crabtree, Norman, and Bingham[32] found that shape perception was not calibrated by haptic feedback in grasping although it has been found that the distance and size perception was calibrated by haptic feedback even for 50% of time[22,23,24]. In addition, although the distance and size perception was recalibrated by distorted haptic feedback[26], the shape perception was not recalibrated by distorted haptic feedback in reaching-to-grasp the object. Lee et al.[32] used the aspect ratio of depth to width of objects as a measure of object shape and grasp apertures during the reach, but before contact with an object to evaluate shape perception. Although they could touch the object every trial, the aspect ratios were accurate when their hand was not occluded (closed-loop condition) compared to when their hand was occluded (open-loop condition). This finding was consistent with previous findings in which feedback failed to calibrate reaches in respect to object shape although it succeeded in respect to object distance and size[22]. Thus, shape perception should be continuously guided online to be accurate.

3. Conclusion

From shape and space perception studies, it has been found that shape perception is poor. We cannot perceive Euclidean 3-D structure accurately. Instead, we perceive non-Euclidean and ordinal relations between physical and perceived space. However, humans can perform complex visually guided actions very accurately in spite of poor shape perception. There have been two prominent theories explaining how actions can be performed accurately without accurate space perception. According to the world model, perception is the relation between physical space and visual space internally represented by the central nervous system. The desired action is produced by the internal model created by the nervous system. Since the internal model calibrates the action by itself, poor shape perception does not affect the action. Thus, after visual space is represented, the desired action is governed by the internal model of the dynamics of action even without continuous perception. For example, it is possible to walk toward the target without vision after initial view of the target.

On the other hand, the control law theory states that perceptual information is relevant to the specific type of action variable. If perception is directly related to action, poor perception should have an effect on the action. The solution denoted by the control law is that perceptual-motor mappings tweak the dynamics of the system for the desired action. For instance, it is possible to walk toward the target without vision during a short period of time, but the feedback should be needed to calibrate distance perception in walking periodically in order to provide accurate walking over longer distances. Although some perceptual-motor mappings could be calibrated by visual or haptic feedback, some could not be calibrated by feedback. Instead, these behaviors required online guidance of the action system. When reaching-to-grasp objects with varying shapes, shape perception is not calibrated by haptic feedback. Instead online, continuous visual guidance is required for accurate reaching-to-grasp behavior.

Recently, artificial intelligence researches are influenced by embodied cognition, a dynamical systems approach, a model of perception and action and so on[33]. Humans are also a part of embodied agents in our environment and this concept has applied to several areas, such as games and intelligence vehicle[34,35]. Thus, it is important to consider interactions with environment and extend this research in various areas.

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